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Two-Layered Microwave Absorber of Ferrite and Carbon Fiber Composite Substrate

Han-Shin Cho and Sung-Soo Kim

Department of Materials Engineering, Chungbuk National University, Cheongju 361-763, Korea

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Microwave absorbing properties of ferrite-epoxy composite (absorbing layer) attached on the carbon fiber polymer composite (reflective substrate) are analyzed on the basis of wave propagation theory. A modified equation for wave-impedance-matching at the front surface of absorbing layer including the effect of electrical properties of the quasi-conducting substrate is proposed. Based on this analysis, the frequency and layer dimension that produce zero-reflection can be estimated from the intrinsic material properties of the absorbing layer and the substrate. It is demonstrated that the microwave reflectivity of carbon fiber composite has a strong influence on the microwave absorbance of front magnetic layer.

1. Introduction

A conventional ferrite absorber in tile or composite form is attached on the existing metal structures and thereby reduce the wave reflections from such a conductive substrate. For this metal-backed (short-circuited) absorber, many studies were carried out to design the zero-reflected absorber and to improve the microwave absorbing properties [1-4]. However, in movable semi-anechoic chamber or other types of moving vehicles, the structures are preferable as light as possible. For this demand, the metal parts can be replaced by carbon fiber polymer composites with high mechanical strength and low weight. Furthermore, the carbon fiber composites, due to its high electrical conductivity, can be used as a microwave reflector [5-7]. Therefore, a two-layered absorber consisting of the ferrite and carbon fiber composite substrate can be proposed as a light-weighted structural absorber having low microwave reflections.

The purpose of this study is to investigate the microwave absorbing properties of ferrite composite attached on the carbon fiber polymer composite substrate. On the basis of wave propagation theory, a modifed equation for wave-impedance-matching at the front surface of absorbing layer is proposed. It is demonstrated that the microwave absorbance of front ferrite-absorbing layer is strongly influenced by the electrical properites of the attached carbon fiber polymer composite.

2. Design of Absorber

Consider a situation that a plane wave illuminates the microwave absorber attached by a quasi-reflective substrate as shown in Fig. 1(a). The situation is analogous to that of terminated transmission line as schematically shown in Fig. 1(b), where Z_0 is free-space impedance (376.7 Ω), Z_{C1} and Z_{C2} are characteristic impedance of substrate and absorber, and $Z_{in(1)}$ and $Z_{in(2)}$ are input impedance at the front surface of reflecting substrate and absorbing layer, respectively.

If the relative permeability and permittivity of the substrate and absorbing layer are designated by μ_{r1}, ε_{r1} and μ_{r2}, ε_{r2} respectively, the characteristic impedance and propagation constant ν_1, ν_2 in the two medium is expressed as

$$Z_{c_1}(substrate) = Z_0\sqrt{\mu_{r_1}/\varepsilon_{r_1}} \tag{1}$$

$$Z_{c_2}(absorber) = Z_0\sqrt{\mu_{r_2}/\varepsilon_{r_2}} \tag{2}$$

$$\nu_1\ (substrate) = j(2\pi f/c)\sqrt{\mu_{r_1}\varepsilon_{r_1}} \tag{3}$$

$$\nu_2(absorber) = j(2\pi f/c)\sqrt{\mu_{r_2}\varepsilon_{r_2}} \tag{4}$$

where f is frequency and c is velocity of light. $Z_{in(1)}$ and $Z_{in(2)}$ are a function of material constants (μ_r, ε_r) and layer thickness (d_1 and d_2 for the substrate and absorber, respectively), expressed as

$$Z_{in_{(1)}} = Z_{c_1} \times \frac{Z_0 + Z_{c_1}\tanh \nu_1 d_1}{Z_{c_1} + Z_0 \tanh \nu_1 d_1} \tag{5}$$

$$Z_{in_{(2)}} = Z_{c_2} \times \frac{Z_{in_{(1)}} + Z_{c_2}\tanh \nu_2 d_2}{Z_{c_2} + Z_{in_{(1)}} \tanh \nu_2 d_2} \tag{6}$$

If the substrate is a perfect conductor ($Z_{in(1)}$=0), Equation (6) reduces to

$$Z_{in_{(2)}} = Z_{c_2}\tanh \nu_2 d_2 \tag{7}$$

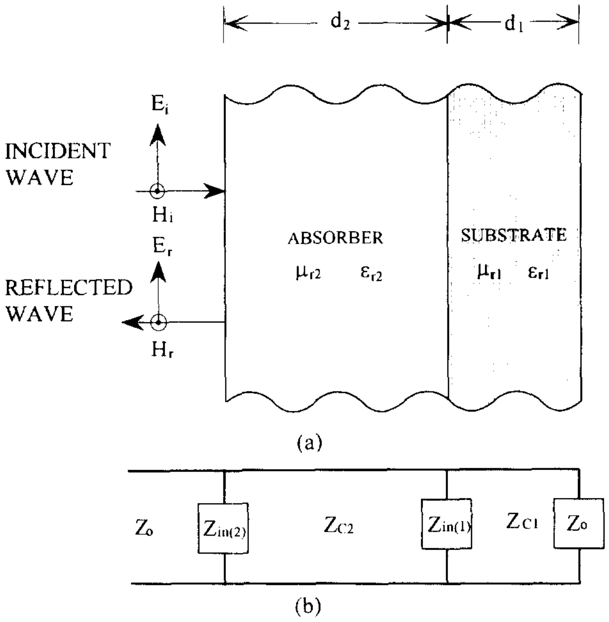

Fig. 1. (a) Plane wave incident normally on the microwave absorber and (b) analogous transmission line.

which is the impedance equation for a mono-layer absorber on metals.

When the wave is incident normally on the boundary beween two media, part of incident wave is reflected while another part is transmitted into the second medium. The amplitude of the reflected wave (E_r) is related to that of the incident wave (E_i) by the reflection coefficient (Γ), defined by

$$\Gamma=(E_r/E_i) \tag{8}$$

The power reflectance, in decibels, is then given by

$$reflection\ \ loss = 20\ \log\ |\ \Gamma\ | \tag{9}$$

For normal incidence, the reflection coefficient at the front surface of the absorbing layer is given by

$$\Gamma=\frac{Z_{in_{(2)}}-Z_0}{Z_{in_{(2)}}+Z_0} \tag{10}$$

In the case of matched line ($Z_{in(2)}=Z_0$), there is no reflected wave from the absorber (Γ=0). Since $Z_{in(2)}$ is a function of not only Z_{c2} and V_2 but $Z_{in(1)}$ as well, the electromagnetic properties and dimension of the reflective substrate influence on the microwave absorbing properties of the front absorbing layer.

3. Experimentals

3.1 Specimen Preparation

The absorbing layer was prepared from the mixture of ferrite filler and epoxy resin. The magnetic lossy material used as a filler was Ni-Zn ferrite. The stoichiometric compound of ($Ni_{0.4}Zn_{0.60}$) (Fe_2O_3) composition was prepared by solid-state reaction at 1250°C in N_2 atmosphere. The mixing ratio of ferrite to resin was 1 in weight (approximately 20 in ferrite vol%). The mixture was molded in a coaxial die with a dimension of 3 mm in inner diameter and 7 mm in out-diameter.

Commercially available carbon fiber-epoxy composites were used as a substrate material. The constituent materials of the composite were 8-harness fabric carbon fibers and bisphenol-A type epoxy resins. The fiber content was about 60 wt%.

3.2 Measurements

The complex permeability and dielectric constant were determined by using HP/8720B network analyzer. Measurements were made in the C- and X-band frequencies (4-12 GHz). The precisely machined toroidal samples were inserted between the inner and outer conductors of standard coaxial line. The complex permeability and dielectric constant were determined from the measured reflected and transmitted scattering parameters [8].

4. Results and Discussion

4.1 Material Constants (μ_r, ε_r)

Fig. 2 shows the complex permeability (μ_r'-$j\mu_r''$) and permittivity (ε_r'-$j\varepsilon_r''$) spectra observed in the ferrite-epoxy composite. In this specimen, $\mu_r'$is nearly constant (about 1) and μ_r'' decreases as the frequency increases (0.63 at 4 GHz, 0 at 12 GHz). Nearly constant value of ε_r' and ε_r''(4.6 and 0.3, respectively) are observed in the frequencies.

Fig. 3 shows the material constants spectra observed in the carbon fiber-epoxy composite specimen. High dielectric constant and considerable loss was observed in this specimen. ε_r' is a decreasing function of frequency and ε_r'' increases with the increase of frequency. Nearly constant value of μ_r'(equal to free-space permeability) was

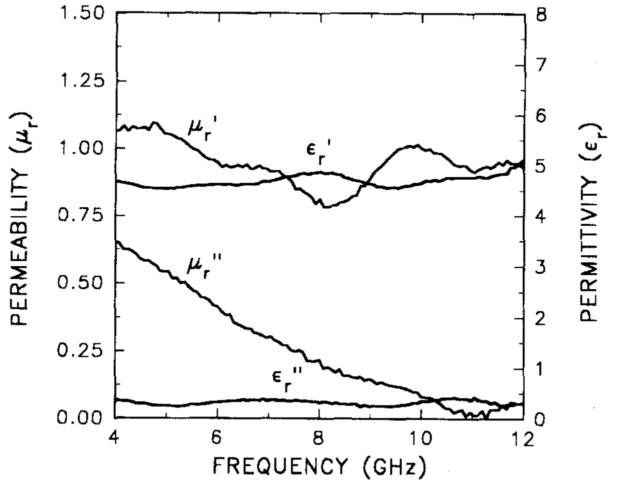

Fig. 2. Complex permeability and permittivity of ferrite-epoxy composite.

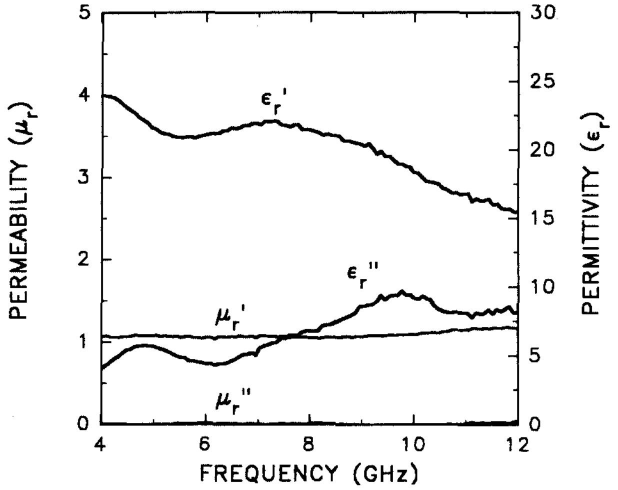

Fig. 3. Complex permeability and permittivity of carbon fiber-epoxy composite.

observed and μ_r'' was negligibly small. Frequency dispersion of dielectric constant of composite specimens containing conductive particles or laminates was explained by Hippel [9]. The space charge polarization between parallel carbon fibers (conductors) seperated by epoxy matrix (insulator) can lead to high dielectric constant. The imaginary part of dielectric constant is coming from the ohmic loss along the longitudinal axis of fibers [5]. The low permeability is due to the nonmagnetic property of the composite.

4.2 Microwave Absorbing Properties

Fig. 4 shows the thickness-dependence of microwave reflection calculated from the material constants of ferrite-epoxy composite on the assumption that the rear face of the sample is terminated by a short-circuit. The equations (7) and (10) were used for the calculation. The reflection loss depends on the layer thickness. Maximum absorption point moves to lower frequency as the thickness increases. However, the reflection loss is no less than − 20 dB in the whole frequencies. Even in a specimen thicker than 6 mm, no more attenuation than − 20 dB was estimated.

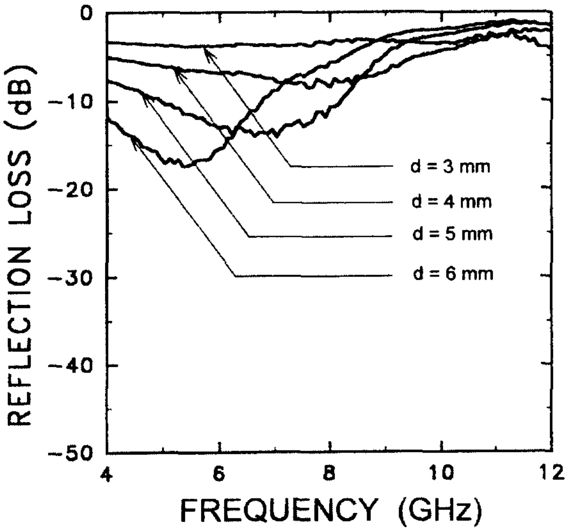

Fig. 4. Reflection loss determined in the short-circuited ferrite-epoxy composite.

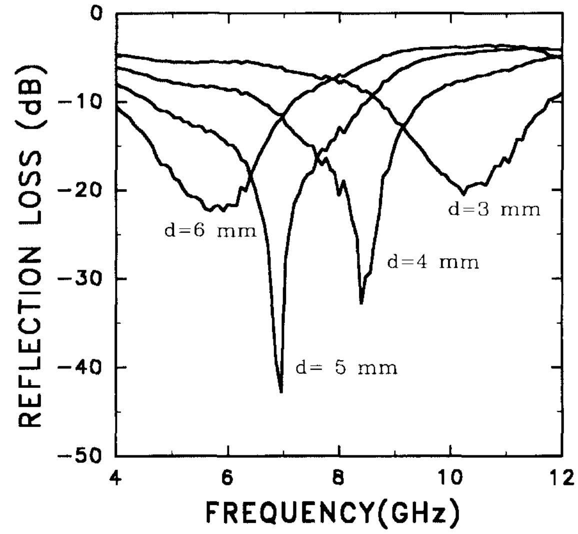

Fig. 5. Reflection loss determined in the ferrite-epoxy composite attached to the carbon-fiber composite.

For the same absorber attached on the carbon-fiber composite, the microwave absorving properties are greatly improved as shown in Fig. 5. The calculation was made using the eqations (6) and (10) with a fixed substrate thickness (d_1=2 mm). The property was best in that thickness. As compared with the reflection loss of metal-backed absorber (Fig. 4), a much reduced microwave reflectance is predicted. The reflection loss in this case is also dependent upon the absorber thickness. The maximum absorption point moves to lower frequency as the thickness increases from 3 mm to 6 mm.

The most reduced reflection loss is predicted in the absorber 5 mm in thickness and at the frequency of 6.9 GHz. The result indicates that the microwave absorbance can be greately improved by the replacing the metals with the quasi-reflective carbon fiber composites as a substrate material.

4.3 Matching Frequency and Matching Thickness

The realization of wave-impedance-matching at the front surface of absorbing layer ($Z_{in(2)}$=Z_0 in Equation (10)) can be investigated by using the Smith chart. Fig. 6 shows the frequency dispersion of input impedance at a given thickness of the substrate (d_1=2 mm) and the absorber (d_2= 5 mm). The locus of input impedance for the metal-backed absorber is also given. In the case of ferrite absorber attached by carbon-fiber composites, the locus of input impedance is crossing the center point (R+jX=1+j0) at 6.9 GHz, where R is normalized resistance and X is normalized reactance with respect to free-space impedance. The matching thickness and matching frequency are, therefore, estimated to be 5 mm and 6.9 GHz, respectively.

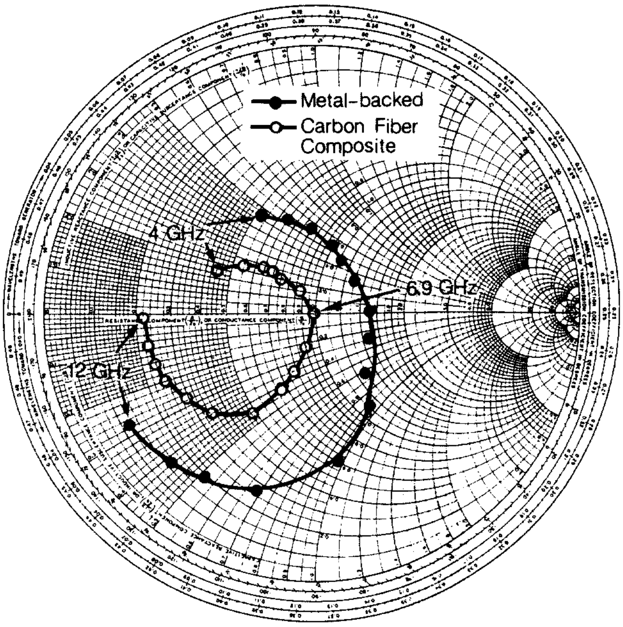

Fig. 6. Impedance locus in Smith chart.

This prediction is in good agreement with the result of reflection loss shown in Fig. 5.

In the case of metal-backed absorber, however, no wave-impedance-matching is evident as shown in Fig. 6. Non-zero impedance at the surface of carbon-fiber composite (therefore, with some transmitted wave) modifies the wave propagation in the front absorbing layer. The input impedance at the surfaces of absorbing layer corrected in this way could be adjusted to be equal to free-space impedance at a specified frequency and thickness. It can thus be suggested that the carbon-fiber composite with non-zero resistance (partial wave reflection) is effectively used to improve the microwave absorbing properties of the front ferrite absorber.

5. Conclusion

This study has demonstrated that the microwave absorbance of ferrite composite can be significantly influenced by the electrical properties of the substrate material. The improvement in microwave absorbing properties could be obtained by replacing the metals with quasi-reflective carbon fiber composite as a substrate material. The result is attributed to the non-zero surface impedance of the carbon-fiber composite. In this way, the microwave absorber for structural application can be produced. Further modification of electrical properties of the substrate may control or promote the microwave absorbing properties of the two-layered absorber.

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